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Monochromatic aberrations in the accommodated human eye

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Abstract

The wave-front aberration of the human eye was measured for eight subjects using a spatially resolved refractometer (a psychophysical ray-tracing test). The eyes were undilated and presented with accommodative stimuli varying from 0 to -6 diopters. Monochromatic wave-front aberrations tend to increase with increasing levels of accommodation, although there are substantial individual variations in the actual change in the wave-front aberration. While spherical aberration always decreased with increasing accommodation, it did not change from positive to negative for every observer. The direction and amount of change in fourth order aberrations varied between observers. Aberrations with orders higher than fourth are at a minimum near the resting state of accommodation. The accommodation induced change in wavefront aberration was not strongly related to the total amount of aberration in the eight eyes studied. © 1999 Elsevier Science Ltd. All rights reserved.

Keywords: Aberration; Accommodation; Wave-front; Eye; Optical quality; Physiological optics

1. Introduction

The optical function of the human eye is to image exterior objects on the retina, where the visual information is encoded by photoreceptors for further processing in the neural system. Principally, only objects at a single distance from the eye are focused at the retina. Objects at farther and/or closer distance are best focused either in front of, or behind the retinal plane, and this deviation of the image plane from the retinal plane is called defocus. The effect of defocus on vision is to make objects appear blurred. In order to see objects at different distances clearly, the eye accommodates, that is, it changes the refractive power and position of the lens and consequently moves the focal plane of the eye's optics.

The quality of the retinal image for objects in focus depends on the optical quality of the eye, which is governed both by its ocular aberrations and by diffraction. For an ideal eye, light passing through the pupil from a single point converges to an area on the retinal plane limited only by diffraction. The rays, however, will be deviated from the ideal image position if the eye is not perfect, and the deviation of any given ray from the ideal point image is called the transverse ray aberration. The orthogonal trajectories of the rays form a wave-front, which will deviate from an ideal spherical surface if the eye has aberration, and the deviation in wave-front is called the wave-front aberration (Born & Wolf, 1983). The wave-front aberrations of the eye are usually described as a two-dimensional surface at the pupil plane. Recently monochromatic wave-front aberration of the eye for a single accommodative condition has been well characterized from measurements using two dimensional ray tracing techniques including subjective and objective aberroscopes (Howland & Howland, 1976, 1977; Walsh, Charman & Howland, 1984; Walsh & Charman, 1985), psychophysical ray-tracing tests (Smirnov, 1961; Webb, Penney & Thompson, 1992; He, Marcos, Webb & Burns, 1998), optical ray tracing techniques (Navarro and Losada, 1997), and objective Hartmann–Shack wave-front sensors (Liang, Grimm, Goetz & Bille, 1994; Liang & Williams, 1997). The wave-front errors for the human eyes have been found to have irregular complex shapes, and change substantially from individual to individual. Among the decomposed individual aberration terms, not only spherical aberration and coma aberrations (Seidel aber-

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rations) have been shown to strongly affect human foveal vision (Ivanoff, 1956; Koomen, Tousey & Scolnik, 1956; Jenkins, 1963; Howland & Howland, 1977; Walsh et al., 1984; Walsh & Charman, 1985; Campbell, Harrison & Simonet, 1990; Atchison, Collins, Wildsoet, Christensen & Waterworth, 1995), but also other asymmetric aberrations and aberrations with order higher than fifth have been shown to contribute substantially to reducing visual performance when the pupil size is large (Liang & Williams, 1997). The various types of aberration in the human eye change from individual to individual in both their sign and amplitude (Howland & Howland, 1976, 1977; Walsh et al., 1984; Liang et al., 1994; Liang & Williams, 1997; He et al., 1998).

The aberrations of the eye can be expected to change when the eye accommodates to targets at various distances. This will happen because in most compound optical systems the aberrations arise both from the optical quality of the individual components, and from misalignment of the relative positions of the different optical elements. Since accommodation is achieved through changes in the shape and position of the lens (Koretz, Bertasso, Neider, True-Gabelt & Kaufman, 1987), the ocular aberrations should vary as well. Study of the change in aberration with accommodation can be traced back two centuries (see review by Koomen et al. (1956), however, 'the exact nature of this change remains to be fully explored.' (Charman, 1991). Atchison et al. (1995) made the first attempt to characterize the wave-aberration of the eye in detail. Using the objective aberroscope technique (Walsh et al., 1984; Walsh & Charman, 1985) they measured aberrations up to the fourth order for three states of accommodation (0, − 1.5 and − 3 diopter). They measured the aberrations in 15 subjects but did not find a clear trend in the amount or direction of change with accommodation. For example, only eight of the 15 subjects showed a classical trend to less positive or more negative spherical aberration as accommodation increased (Ivanoff, 1956; Koomen et al., 1956; Van den Brink, 1962; Jenkins, 1963). For the other seven subjects, three showed a maximum positive, and three a maximum negative value for the − 1.5 D level, one subject even had the spherical aberration change in a way against the classical trend. For other individual aberrations such as coma, no information is available in their report. The variance of the wave-front, which is related to the overall optical quality of the eye, did change with accommodation for many observers, showing a maximum or a minimum in its variance for the − 1.5 D level.

From a reanalysis of the data by Van den Brink (1962) for one subject in accommodation ranging from 0 to − 1 D, Howland and Buettner (1989) suggested a diminution in the magnitude of coma-like aberration with accommodation. By using a near-infrared double-pass apparatus, Lopez-Gil, Iglesias and Artal (1998) found the double-pass image for the accommodated eye tends to be more symmetric than for the unaccommodated eye. This change was suggested to arise from a decrease in the amount of coma-like aberration or to an increase of other symmetric aberrations. Lu, Munger and Campbell (1993) examined third and fifth order spherical aberration and coma for five accommodative states ranging from − 0.5 to 4 diopter for three subjects. The third and fifth order spherical and coma aberrations were found to change significantly with accommodation, and the fifth order aberrations were suggested to balance the third order aberrations. Their measurement, however, was along a single x-axis in the pupilary plane, and therefore no information on the change in either the overall wave-front aberration or individual aberration terms could be obtained.

In summary, the optical performance of the eye at different accommodative conditions is not well characterized, and the total range of accommodative states that has been analyzed is limited. The advent of improved analysis and measurement techniques for studying the optics of the eye in recent years makes it now feasible to measure the change in imaging performance of the eye in detail. To obtain these measurement we chose to use a subjective, psychophysical, technique, which permits the use of lower light levels, and consequently a fairly large pupil, but without the use of mydriatics. The subjective technique first introduced by Smirnov (1961) for testing the human eye by spatially examining the refractive performance of light rays point by point across the entire pupil has not been widely adopted in the study of aberrations of the eye because it has traditionally been time consuming. A faster implementation of Smirnov's technique was developed by Webb et al. (1992), and called the spatially resolved refractometer. A new version of the spatially resolved refractometer (He et al., 1998) allows rapid estimates of both the overall wave-front aberration and individual aberrations (described using a Zernike polynomial expansion, see Malacara, 1992, up to the seventh order). In the present paper we used this modified technique to measure the change in aberrations over a 6 diopter range for eight subjects.

2. Methods

2.1. Apparatus

The wave-front aberration of the eye to different accommodative stimuli was measured using the spatially resolved refractometer described by He et al. (1998). Briefly, the technique adopts a ray-tracing principle. Due to aberrations parallel light rays entering the eye through different locations in the pupil will not cross the retina at the same location. This deviation in the retinal location can be measured by sequentially selecting different positions in the pupil, and nulling the displacement by tilting the measurement beam until it is aligned to a reference stimulus. The required tilts are the derivative of the wave-front aberration of the eye. In the spatially resolved refractometer we make these measurements by selecting 37 different entry pupil positions, and aligning a point source imaged through those pupils to a reference target provided by a separate optical channel which enters the eye through a fixed pupil location.

The apparatus is a three channel optical system, including a test channel, a reference channel and a pupil monitoring channel. In the test channel, a reflected divergent beam from a 12 mm steel ball was formed by reflection of a collimated beam from a laser source (543 nm). The divergent beam was further reflected by a gimbaled mirror (Fourwad Technologies). The angle of the mirror, hence, the direction of the test beam was controlled by an analog joystick. The center of the steel ball is conjugated to the subjects' retina, and thus appears as a small test spot for the subject. Adjusting the direction of the joystick allows the subject to change the angle at which the test beam enters the eye, and consequently, to move the small spot on the retinal plane. The test beam enters the eye through an artificial aperture with a 1 mm diameter. During the experiment, the location of the aperture was randomly changed from trial to trial among 37 sampling locations that tile the eye's pupil.

The reference position for aligning the test spot was provided by a reference channel, where a cross target was conjugated to the retinal plane of the eye. The center of the cross was used as the point to which the test spot in the test channel was aligned. Superimposed on the cross target was a slide full of letters, curves and lines with different sizes. This complex image subtended roughly 10° and provided a stimulus for accommodation. In the reference channel, a green filter was used to select wavelengths approximately matched to the test channel. The size of the entrance pupil for the reference channel was varied by means of an iris diaphragm. For initial measurement of the resting position of accommodation this was set to 1 mm (see below). For all other measurements the reference channel entrance pupil was set to 8 mm diameter. This large pupil size helped to minimize the depth of focus of the eye. The use of the large reference pupil does introduce a potential difference in the average ray aberrations (tilt) of the eye between the reference channel and the centered 1 mm sampling pupil. However, since tilt does not change the image quality of the eye, we do not include tilt in any of the analyses presented.

The pupil position was continuously monitored with an infrared sensitive CCD video camera. The subject's bite bar was mounted on a three dimensional (X, Y, Z) translator which served to keep the subject's pupil aligned to the optical axis of the instrument.

In addition, a set of mirrors mounted on a movable stage was positioned on a common pathway for the three channels, and formed a Badal system for correcting refractive error and/or introducing different accommodative stimuli. This Badal set-up provides a change of refractive power in a range from 0 to -6 diopter.

2.2. Subjects

Eight subjects participated in this experiment, including six females (AB, KK, CA, LT, KM, SM, ages, 28, 27, 27, 24, 26 and 27, respectively) and two males (JH and CK, ages 38 and 35). While subjects JH, CK, and AB are emmetropes, the rest of the subjects are myopes with spherical error from -2 to -5.56 D. None of these subjects has a record of ocular disease. Only the right eye was tested.

2.3. Procedure

The measurement consisted of a practice session and three data collection sessions on separate days. In each session, seven accommodative conditions, corresponding to the accommodative stimuli ranging from 0 to -6 diopter in steps of one diopter, were tested in random order. Each condition consisted of 39 trials. For the first and the last trials, the test light entered the center of the pupil. The other 37 trials sampled the entire pupil in random order (see He et al., 1998).

The subject was first aligned to the optical system. Spherical error was then measured by moving the stage on the common pathway until the stimulus target appeared in focus for the subject. This test was made with an entrance aperture for the reference channel of 1 mm diameter, and thus provided an estimate of the resting state of accommodation. For emmetropes, the position is in the range of -1 to -1.5 diopter (an external distance of 1 m or less). For myopic subjects whose resting point fell outside this range a trial lens was introduced at a pupil conjugate position so that the resting position fell between -1 and -1.5 diopters on the Badel optometer. A complete measurement session for a single accommodative condition usually lasted about 3 min. A whole session (seven conditions) required about a half hour.

During the measurement, the subject's pupil was always monitored and adjusted to maintain the alignment to the optical system and an adequate size of the pupil[2]. Data analysis was not possible for two of the subjects (KM, LT) at −6 D and one of the subjects (AB) at both −5 and −6 D due to accommodation induced pupillary constriction producing a pupil diameter less than 6 mm.

2.4. Data analysis

The changes in entrance angle of the test beam recorded by the computer are the measures of the slope of the wave-front at the 37 pupil locations. A least square procedure(Cubalachini, 1979) written in MATLAB was used to fit the slope measurements to the derivatives of 35 terms of the Zernike polynomials. We use the derived coefficients to provide estimates of the weight of individual aberrations, and reconstruct the over all wave-front aberration. The fourth Zernike term, the defocus term, was taken as a measure of the accommodative response. All analysis routines were written by us in Matlab (Mathworks, Natick, MA). The measurement technique and analysis routines were validated as described in He et al. (1998).

3. Results

3.1. Accommodative responses

In order to confirm that the eye under test was effectively responding to accommodative stimuli during the experiment, the defocus term was checked. The accommodative response functions for all eight subjects are illustrated in Fig. 1. The responses for different subjects are indicated with different symbols. The three empty symbols represent responses for the three emmetropic subjects, the five solid symbols show myopic subject's responses. The dashed line in Fig. 1 represents the results that would be obtained with an accommodation system that perfectly tracked the stimulus. Responses above the theoretical line indicate that the eye is over-accommodated, and responses below the dashed line indicate that the eye is under-accommodated. Results in Fig. 1 show an over accommodation for low accommodation levels and an under-accommodative response at higher levels for all subjects. These responses are typical for the human accommodation system (Morgan, 1944), and thus, indicate that the eyes were accommodating normally during our experiment.

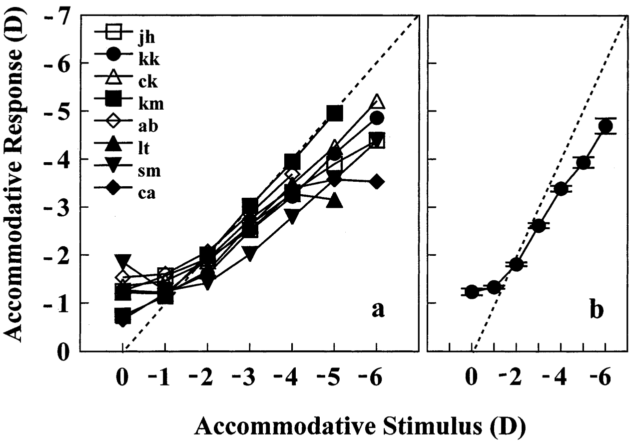

Fig. 1. The accommodative responses of eight subjects (a) and the averaged response (b) as functions of accommodative stimulus. The accommodative response was calculated from the defocus term of the Zernike expansion. The response for each subject is represented with different symbols in panel a. The error bar in panel b indicates ±1 S.E.M. The dashed lines show the theoretical predictions for an ideal accommodative system.

3.2. Change in overall wave-aberration with accommodation

Fig. 2 shows contour maps of the wave-front aberration for three subjects at each accommodative conditions. The horizontal and vertical axis indicate a coordinate (in mm) on the pupil plane from nasal to temporal and from inferior to superior, respectively. Each contour line shows the locations where the measured wave-front deviated from an ideal planar wave-front by a constant amount, and the change in wave-front height between any two lines is 1 μm. It is clear from Fig. 2 that there is a change in wave-front aberrations with accommodation for all three subjects. The effect of accommodation on the wave-front, however, varies markedly from individual to individual. While subject JH and CK show an increase in aberrations with accommodation, subject SM changes from 0 to −1 D, but very little for the rest of the conditions.

Fig. 3 shows the effect of accommodation on the root-mean-square (RMS) wavefront aberration for all eight subjects. The RMS wave-front error provides a general estimate of the variation of the wave-front from ideal. The higher the RMS wave-front error, the larger the wave-front aberration and the worse the image quality. Symbols represent the mean RMS wave-front error from three measurements. The standard error of the mean across sessions was typically smaller than a symbol (mean S.E. = 0.15 μm). In general, as shown in

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[2] We used a pupil diameter of 7.33 mm for all calculations, since this diameter represents the furthest position within the system from which a light ray can enter the eye. However, in practice, while we required that subject's pupils be larger than 6 mm, they were typically less than 7 mm for higher levels of accommodation. To determine whether this difference between the actual pupil and the pupil size used to normalize the Zernike coefficient affected the data, we used a simulation program written in MATLAB. We first generated a known wave-front over the entire 7.33 m pupil. Next we sampled that pupil, assuming that the eye's pupil was 6.25 mm. We then used the sampled pupil to calculate a new, sampled, set of Zernike coefficients. The difference between the original and resampled coefficients was less than the standard deviations of our settings.

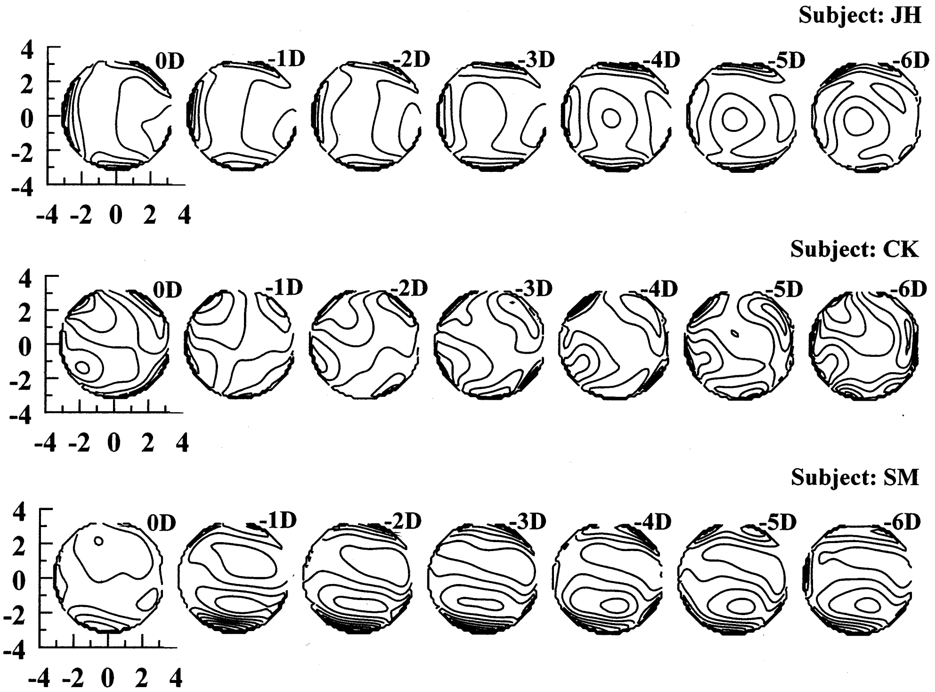

Fig. 2. Contour maps of wave-front aberrations under the seven accommodative conditions for three subjects. The contribution from defocus has been excluded. Lines are plotted at 1 μm intervals in the pupil plane. The horizontal and vertical axis indicate the coordinate of the pupil from nasal to temporal and from inferior to superior, respectively.

Fig. 3a, there is a change in RMS wave-front error with accommodation for all subjects, but the sign and amplitude changes from individual to individual. Fig. 3b shows the average for the eight subjects with the error bars indicating ± 1 S.E.M. The average RMS wave-front error decreases between 0 and − 1 D, remains the same between − 1 and − 3 D, then gradually increases again for higher accommodation levels.

3.3. Change in individual aberration terms with accommodation

Fig. 4 compares the 35 individual Zernike coefficients for subjects JH for the − 1 D (●) and − 4 D (◆) accommodative conditions. Error bars represent ± 1 S.E.M. The first order of the Zernike terms, corresponding to tilts in the X and Y directions are not shown. Some of the higher order Zernike terms can be related to classical optical aberrations. For instance, terms 3–5 are the second order Zernike terms, which represent astigmatism at 0 and 90° (term 3) and 45° (term 5) and defocus (term 4). Terms 7 and 8 are third order Zernike coefficients representing the X- and Y-axis coma, respectively. Term 12 is a fourth order Zernike term, representing primary spherical aberration. Fig. 4 shows a significant change with accommodation in both primary spherical aberration and coma-like aberrations for this subject.

Fig. 5 shows the change in primary spherical aberration with accommodation for all eight subjects, where measurements for individual subjects are shown in panel a and the average in panel b. Spherical aberration decreased with accommodation for all subjects. While the average results, as shown in panel b, indicate a change of the coefficient value from positive to negative, this pattern does not hold for every individual. For example, subjects JH and CK always have a negative value, and subject LT always has a positive coefficient.

Fig. 6a shows the changes in coefficient 8 (y-axis coma) with accommodation for eight subjects and the

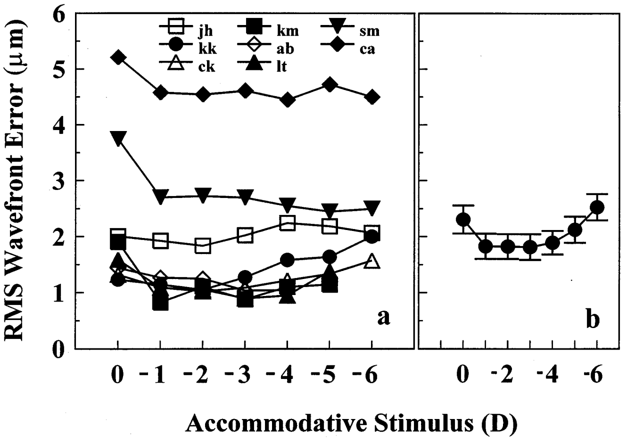

Fig. 3. The root-mean-square (RMS) of the wave-front error for the seven accommodative conditions for eight subjects (a) and the average (b) in microns. The defocus term is excluded. The individual results are represented with different symbols as in Fig. 1. The error bars in panel b indicate ± 1 S.E.M.

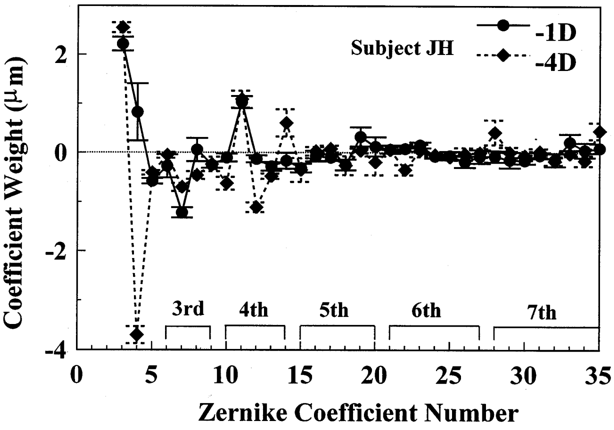

Fig. 4. Coefficient distribution of the 35 Zernike terms measured for the − 1 and − 4 D accommodative stimuli from subject JH. The solid circle and solid line represent the coefficients under − 1 D, and the solid diamond and dashed line indicate coefficients under − 4 D accommodative stimulus. The order of the Zernike functions is indicated by brackets and numbers.

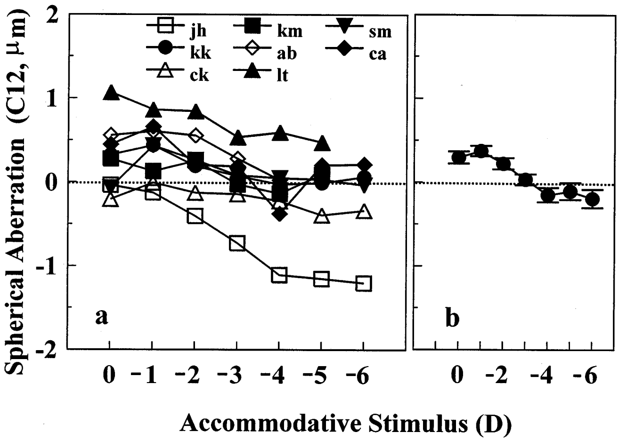

Fig. 5. Spherical aberration as a function of the accommodative stimulus for eight subjects (a) and the average (b). Different symbols represent individual subjects, as in Fig. 1, and the error bar in panel b shows the ± 1 S.E.M.

average are shown in Fig. 6b. Subjects SM and CA show larger negative values (− 1.84 and − 2.80 μm, respectively) than the other subjects at the 0 D stimulation condition. While subject SM shows only a modest change in the *y*-axis coma over the 6 D accommodative range, subjects CA and JH increase markedly with increasing accommodation. However, on average (Fig. 6b) there is no significant trend in *y*-axis coma as accommodation increases. Similar effects are seen for the other 3rd order terms.

Fig. 7 shows the total contribution of aberrations of the 5th, 6th and 7th order as a function of accommodation. It is clear that both the individual results (Fig. 7a) and the average results (Fig. 7b) show a systematic change. The RMS wave-front error decreases as the accommodative stimulation changes from 0 to − 1 D, then reaches a minimum around − 2 D, and increases afterward with further accommodative demand.

4. Discussion

We have measured the monochromatic wave-front aberration for seven accommodative conditions ranging from 0 to − 6 D for eight subjects with the natural pupil. We showed that there were significant and systematic changes in the wave-front with accommodation. In general, we found that the optical quality of the eye improves from 0 to − 1 D and then gradually decreases at higher accommodation levels producing the best image near the resting point of accommodation. This result differs from the results of Atchison et al. (1995) that there was no clear trend in the change in

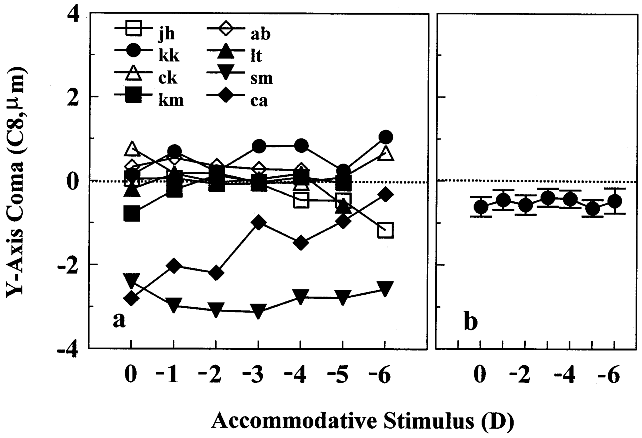

Fig. 6. The *y*-axis coma for eight subjects (a) and the average (b) as a function of the accommodative stimulus. Different symbols represent individual subjects, as in Fig. 1, and the error bar in panel b represents ± 1 S.E.M.

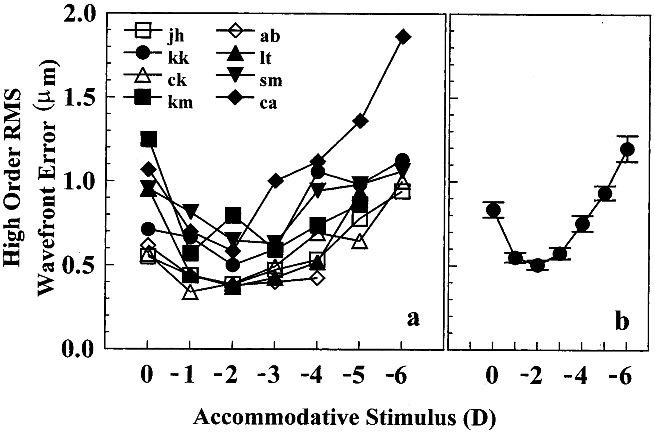

Fig. 7. The RMS wave-front error for the fifth through seventh order as a function of the accommodative stimulus for eight subjects (a) and the average (b). The RMS of wave-front error is plotted in microns. The individual result is represented with different symbols as in Fig. 1. The error bar in panel b indicates ± 1 S.E.M.

wave-front aberrations with changes in accommodation between 0 and −3 D. In their study, no clear trend for the effect of accommodation on wave-front aberrations was found for 15 subjects while our study found a trend. We did find similar large individual differences between observers. For example, subjects JH and CK have a clear change of wave-front aberration over the accommodative range, subject SM, however, changes very little other than between 0 and −1 D. Overall however, our use of a larger range of accommodative stimuli reveals that there is a consistent trend in the change of aberrations with changes in accommodative level.

The total change in wave-front aberration with accommodation varies less across subjects than the absolute difference between subjects, and seems to be fairly similar in magnitude from one subject to the next. For instance, both SM and CA, who have the largest total wave-front aberration, have similar accommodation related changes in their wave-fronts to the other subjects. Subject KK has very little wave-front aberration, but has the largest relative change in RMS wave-front error, from her lowest value of 1.05 μm at −2 D to her highest 2.00 μm at −6 D. The difference is only 0.95 μm but represents a doubling of her total aberrations with accommodation. This limited change in wave-front aberration with accommodation may partly explain the apparent individual variations in change of wave aberration with accommodation, the changes are more noticeable in an eye with good optical quality.

Changes in individual aberrations have been examined in a number of studies (Ivanoff, 1956; Koomen et al., 1956; Van den Brink, 1962; Jenkins, 1963; Howland & Buettner, 1989; Lu et al., 1993; Atchison et al., 1995). A decrease in spherical aberration with accommodation was always found for the subjects in this study as shown in Fig. 5a, and the change is consistent with the classical trend (Ivanoff, 1956; Koomen et al., 1956; Van den Brink, 1962; Jenkins, 1963) of changing from positive to negative. The change in spherical aberration, however, does not necessarily cross through zero, even though this is true for the average of the eight subjects we tested (Fig. 5b). We did not find a pattern of the change in spherical aberration with accommodation as complex as found by Atchison et al. (1995). The change in coma is not as simple as in the case of spherical aberration, and it shows a complex pattern that varies across individuals as shown in Fig. 6. For example, while subject CA shows a reliable and reproducible increase in the y-axis coma with accommodation, subject JH shows a decrease, and for other subjects there is not a significant change. The average over the eight subjects, as shown in panel b, gives no significant change with accommodation. A similar result was found for x-axis coma also. These results, systematic changes in spherical aberration, and variable changes in coma with increasing accommodation are consistent with motion of the lens during accommodation. That is, the variable coma could arise from a lateral displacement of the lens relative to the cornea, as the lens moves in the accommodation process.

The overall aberrations with order higher than the fourth change similarly for all individuals. The aberrations apparently reach a minimum around the resting state of accommodation, and increase as the accommodative stimulus varies from that position in both directions. This is one of the most consistent trends we find, other than the direction of change in spherical aberration. It suggests that these higher order aberrations are closely correlated to the overall accommodative effort and contribute significantly to the decreased image quality with marked accommodation.

In conclusion, we have investigated the effect of accommodation over a six diopter range on the optical quality of the human eye. We find that the overall optical quality of the eye is best at the resting point of accommodation. Aberrations increase for targets both nearer and farther from the eye. This suggests that a part of the aberrations are rising from the distortion of the lens due to the process of accommodation. However, we also find that accommodation produces significant changes in coma, although the direction of the change varies across individuals. These changes are consistent with changes in the relative centering of the lens and cornea, which probably occur as the lens moves during accommodation (Drexler, Baumgartner, Findl, Hitzenberger & Fercher, 1997).

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